

CATALYZED COMBUSTION IN MICRO-PROPULSION DEVICES – PROJECT STATUS

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INTRODUCTION

In recent years, there has been a tendency toward shrinking the size of spacecraft. New classes of spacecraft called micro-spacecraft have been defined by their mass, power, and size ranges [1]. Spacecraft in the range of 20 to 100 kg represent the class most likely to be utilized by most “small sat” users in the near future. There are also efforts to develop 10 to 20 kg class spacecraft for use in satellite constellations. More ambitious efforts will be to develop spacecraft less than 10 kg, in which MEMS fabrication technology is required. These new micro-spacecraft will require new micro-propulsion technology. Although micro-propulsion includes electric propulsion approaches, the focus of this proposed program is micro-chemical propulsion which requires the development of micro-combustors. As combustors are scaled down, the surface to volume ratio increases. The heat release rate in the combustor scales with volume, while heat loss rate scales with surface area. Consequently, heat loss eventually dominates over heat release when the combustor size becomes smaller, thereby leading to flame quenching. The limitations imposed on chamber length and diameter has an immediate impact on the degree of miniaturization of a micro-combustor. Before micro-combustors can be realized, such a difficulty must be overcome. One viable combustion alternative is to take advantage of surface catalysis.

Micro-chemical propulsion for small spacecraft can be used for primary thrust, orbit insertion, trajectory-control, and attitude control. Grouping micro-propulsion devices in arrays will allow their use for larger thrust applications. By using an array composed of hundreds or thousands of micro-thruster units, a particular configuration can be arranged to be best suited for a specific application. Moreover, different thruster sizes would provide for a range of thrust levels (from μN 's to mN 's) within the same array. Several thrusters could be fired simultaneously for thrust levels higher than the basic units, or in a rapid sequence in order to provide gradual but steady low-g acceleration. These arrays of micro-propulsion systems would offer unprecedented flexibility and redundancy for satellite propulsion and reaction control for launch vehicles.

A high-pressure bi-propellant micro-rocket engine is already being developed [2] using MEMS technology. High pressure turbopumps and valves are to be incorporated onto the rocket “chip”. High pressure combustion of methane and O_2 in a micro-combustor has been demonstrated without catalysis, but ignition was established with a spark. This combustor has rectangular dimensions of 1.5 mm by 8 mm (hydraulic diameter 3.9 mm) and a length of 4.5 mm and was operated at 1250 kPa with plans to operate it at 12.7 MPa. These high operating pressures enable the combustion process in these devices, but these pressures are not practical for pressure fed satellite propulsion systems. Note that the use of these propellants requires an ignition system and that the use of a spark would impose a size limitation to this micro-propulsion device because the spark unit cannot be shrunk proportionately with the thruster.

Currently, cold gas and small monopropellant N_2H_4 systems represent the state-of-the-art in micro-propulsion. It is generally recognized that reduced-scale versions of these conventional systems will not be practical for micro-satellites. In addition, these propulsion systems will benefit greatly from the use of non-toxic propellants, which will require ignition. Systems fabricated using MEMS technology and catalyzed ignition/combustion are proposed. Once catalyzed ignition is established in a microtube, the reacting gases can be used for micro-propulsion device or they can be propagated into the combustion chamber for ignition in larger thrust class rockets. This benefits all rocket propulsion systems through the elimination of high voltage electrical discharges to achieve spark ignition.

Results presented in this paper consist of an experimental evaluation of the minimum catalyst temperature for initiating/supporting combustion in sub-millimeter diameter tubes. The tubes are resistively heated and reactive premixed gases are passed through the tubes. Tube temperature and inlet pressure are monitored for an indication of exothermic reactions and composition changes in the gases.

CHARACTERIZATION OF GASEOUS H_2/O_2 COMBUSTION

Figure 1 plots the spatially resolved profiles of temperature and heat release rate for an atmospheric, freely-propagating, stoichiometric H_2/O_2 flame in the flame coordinates, which are computed using a detailed mechanism of Mueller *et al.* [3]. The corresponding laminar flame speed is 1029 cm/s. It is seen from Fig. 1 that the overall flame thickness based on the temperature profile is of sub-millimeter. If we define the reaction zone thickness as the

full-width-half-maximum of the heat release profile, the corresponding reaction zone thickness is 0.16 mm. Hence, it is expected that a minimum size for micro-combustors using stoichiometric H_2/O_2 premixed combustion would be limited to 0.1 mm, below which the flame is expected to be quenched due to excessive loss to the wall.

To further demonstrate the above concept, we have carried out numerical experiments on flame propagation in various two-dimensional channels. The numerical tool chosen for this study is the SPARK Navier-Stokes Code [4], with 2nd-order accurate MacCormack explicit predictor-corrector scheme. The two-dimensional channel is 10 cm in length, and is closed at the left-hand side, while open at the right-hand side. Initially, the channel is filled with an atmospheric stoichiometric H_2/O_2 mixture at 300 K. No-slip wall is assumed and the wall temperature is fixed at 600 K. Ignition is achieved using a 0.6 mm zone (full channel height) of H_2O at 4000 K and 1 atm.

Figure 2 shows the temperature contours for the 1.0 mm \times 10 cm channel at time of 61.6 μs . It is seen that the maximum flow field temperature is greater than 3000 K, indicating that combustion is fairly completed within the present combustor volume. Additionally, at $t=61.6 \mu s$, the propagation front is near the channel exit. Furthermore, the present condition actually leads to detonation. The results clearly demonstrate that for the given premixture stable combustion can be established with a channel height of 1.0 mm.

When the channel height is reduced to 0.1 mm, which is comparable with the characteristic reaction zone thickness, Fig. 3 shows that flame propagation cannot be sustained. Especially, the ignition front eventually dies out. Further increasing the ignition zone to 6 mm length shows no change in results. These results substantiate the concept that a simply scaled-down micro-combustor will be limited by the quenching distance, which is an intrinsic property of the given fuel/oxidizer mixture.

A plot of H_2/O_2 flame thickness as a function of equivalence ratio for atmospheric pressure and pressure of 34.5 kPa (approximately 5 psia) is given in Fig. 4. It is seen that flame thickness increases with decreasing pressure and the calculated flame thickness at the test pressure of 34.5 kPa and an equivalence ratio of 10 (mixture ratio $MR=0.8$) is 4 mm, which is greater than the diameter of either the 0.4 mm platinum or the 0.8 mm palladium micro-tubes used in this catalytic micro-combustion experiment.

Figure 4 also shows the corresponding reaction zone thickness. At the equivalence ratio of 10 (mixture ratio=0.8), the reaction zone thickness is ~ 1 mm at atmospheric pressure and initial temperature of 300 K and increases to ~ 3 mm when the pressure is reduced to 34.5 kPa. Experimental tests in the micro-tubes were run mostly between 1.2 and 0.4 mixture ratios (equivalence ratios of 6.7 to 20, respectively). At these mixture ratios and the low pressure of the tests the reaction zone thicknesses are greater than the diameter of either the 0.4 mm platinum or the 0.8 mm palladium micro-tubes used in this catalytic micro-combustion experiment.

The rich flammability limits of the H_2/O_2 flames at various pressures are compared in Fig. 5. At a given pressure, it is seen that the burning rate decreases with increasing equivalence ratio. The turning point, beyond which steady flame propagation is not possible, defines the rich flammability limit. We further note that for near rich limit hydrogen flames, in which the Lewis number is greater than unity, pulsating instability has been observed to take place in mixtures with fuel concentrations slightly below that of the rich limit [5-7] and the flame was found to oscillatorily extinguish well ahead of the static extinction limit [6,7]. Thus, the flammability range of a H_2/O_2 mixture is expected to be narrowed when the intrinsic oscillatory nature of flame propagation is taken into account.

APPARATUS AND TEST PROCEDURES

Miniature flame tube apparatus is chosen for study because microtubes can be easily fabricated from known catalyst materials and their simplicity in geometry can be used in fundamental simulations to more carefully characterize the measured heat transfer and pressure losses for validation purposes. Experimentally, we investigate the role of catalytically active surfaces within microtubes, with special emphases on ignition and extinction. The experimental apparatus involves the microtube, along with a mass flow control system, electrical power supply to heat a section of tube, and a data acquisition system. A schematic of the instrumented microtubes is shown in Fig. 6. Two capillary tubes were available for testing. One was a 0.4 mm I.D. platinum tube with a 0.15 mm wall thickness and an overall length of 100 mm of which 70 mm was resistively heated. The other tube was 0.8 mm I.D. and was made of palladium with a wall thickness of 0.1 mm and an overall length of 190 mm of which 160 mm was resistively heated. Three thermocouples were spot welded to the outside of the tubes at the 20%, 50%, and 80% positions of the heated section as shown in the schematic. The tubes were tested in a small rocket test facility at the NASA Glenn Research Center. The facility maintains an ambient pressure of 1.38 kPa during the tests. These initial tests were conducted with gaseous oxygen and gaseous hydrogen propellants at low mixture ratios (high equivalence ratios) to test the rich flammability limits of the propellants, to avoid melting the catalysts and to avoid oxidation loss of catalyst material. These propellants are non-toxic and can be produced on-orbit by water electrolysis [8].

PRELIMINARY EXPERIMENTAL RESULTS

Experimental results consist of a determination of the minimum catalyst preheat temperature for initiating/supporting combustion in the two sub-millimeter diameter tubes. Data are obtained with the tubes resistively heated by the power supply in voltage control mode and with reactive premixed gases passed through the tubes. Tube temperature and inlet pressure are monitored for an indication of exothermic reactions and composition changes in the gases.

Temperature data for the 0.8 mm I.D. tube preheated to a peak temperature of 477 K and showing an exothermic reaction is given in Fig. 7. The total mass flow is 0.00123 g/s of gaseous oxygen and gaseous hydrogen at an oxidizer to fuel mixture ratio of 0.8 (equivalence ratio 9.92). The resistivity of palladium at these temperatures is $17.2 \times 10^{-8} \Omega\text{-m}$ and the voltage drop across the tube is 1.21 Volts, giving an estimated power input of 15 Watts. At 10 seconds into the test TC1 has dropped to 338 K, TC2 has dropped to 412 K as the gas picks up heat, but TC3 has risen to 511 K as the gases are heated by catalyzed reactions between TC2 and TC3. At 10 seconds into the test TC3 starts a rapid rise to 750 K. Heat from this reaction is conducted through the tube upstream toward TC2 which starts a rapid temperature rise to 815 K at 16 seconds into the test. Further conduction to the TC1 position is indicated by its rapid temperature rise at 40 seconds into the test. Steady state is reached at TC3 at approximately 60 seconds into the test. The test was terminated at 100 seconds, however, before steady state was reached at TC1.

Temperature data for the 0.8 mm I.D. tube preheated to a peak temperature of 422 K and showing no reaction is given in Fig. 8. The total mass flow is 0.00123 g/s of gaseous oxygen and gaseous hydrogen at an oxidizer to fuel mixture ratio of 0.8 (equivalence ratio 9.92). Some reactions between TC2 and TC3 cause the temperature of TC3 to rise to a peak of 430 K at 6 seconds into the test, otherwise all of the temperatures fall to a steady state profile of TC1 at 321 K, TC2 at 351 K, and TC3 at 377 K.

Data at other mass flows and fuel rich mixture ratios are shown on mass flow rate versus preheat temperature plots in Fig. 9 for the 0.8 mm I.D. palladium tube and Fig. 10 for the 0.4 mm platinum tube. Using temperature and pressure rise as an indication of reactions the solid symbols indicate those test conditions where reactions were observed. As mass flow decreases the preheat temperature required to initiate reactions decreases. For the 0.8 mm palladium tube the lowest preheat temperature for reactions was 340 K at a mixture ratio of 0.8 and a mass flow of 0.000128 g/s. Above a mass flow of 0.0022 g/s reactions did not occur at any preheat temperature in the 0.8 mm I.D. palladium tube, 190 mm long with 160 mm resistively heated. For the 0.4 mm I.D. platinum tube, the lowest preheat temperature for reactions was 480 K at a mixture ratio of 1.0 and a mass flow of 0.000187 g/s. Above a mass flow of 0.00054 g/s reactions did not occur at any preheat temperature in the 0.4 mm I.D. platinum tube, 100 mm long with 70 mm resistively heated.

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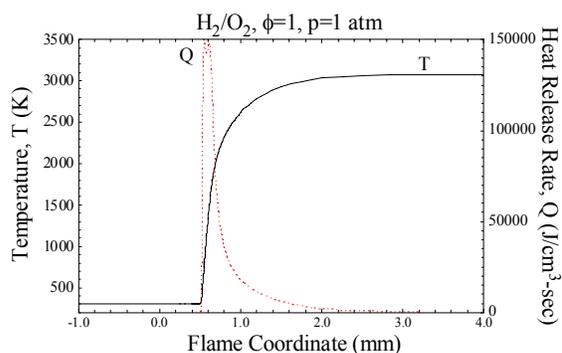


Figure 1. Spatially resolved profiles of temperature and heat release rate of an atmospheric stoichiometric H_2/O_2 flame with initial temperature of 300 K.

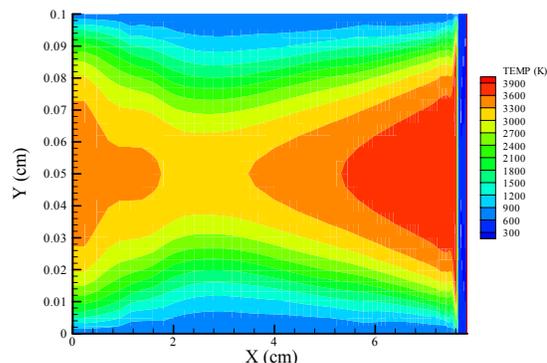


Figure 2. Temperature Contours from closed end of tube through the combustion zone at $t=61.6 \mu\text{s}$, for the case of 1.0 mm channel height.

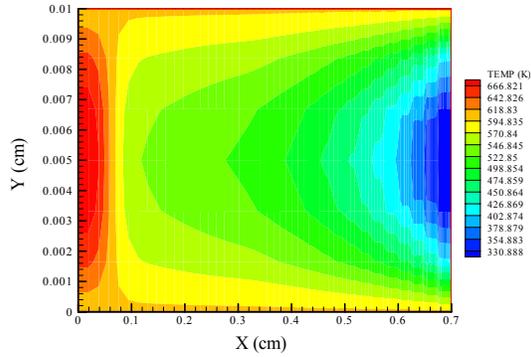


Figure 3. Temperature Contours at $t=4.6 \mu s$, showing no incipient combustion, for the case of 0.1 mm channel height.

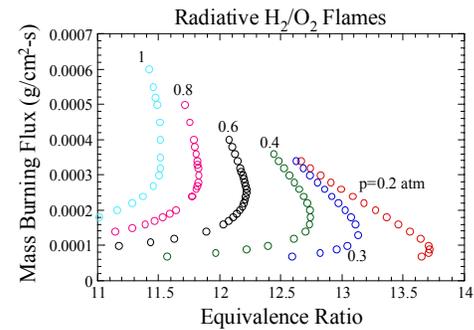


Figure 5. Plot of mass burning flux versus equivalence ratio for rich H_2/O_2 flames at various pressures. The turning point of the response curve defines the rich flammability limit.

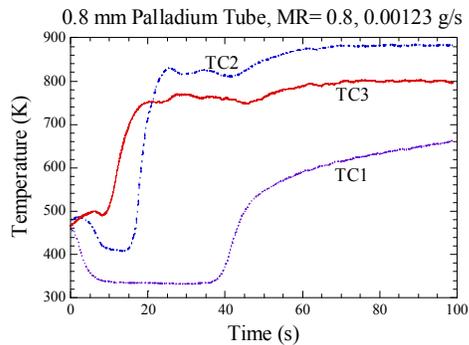


Figure 7. Temperature data for 0.8 mm I.D. palladium tube, $MR=0.8$, 0.00123 g/sec.

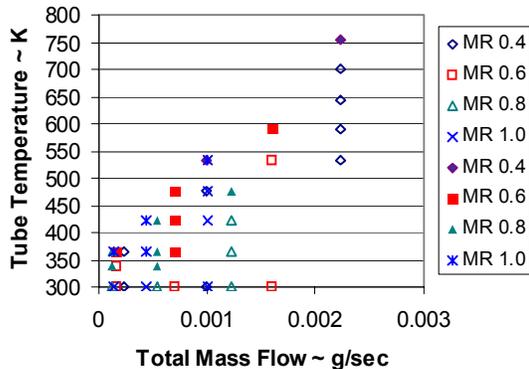


Figure 9. Ignition data for 0.8 mm I.D. palladium tube – open symbols are non-ignition and solid symbols are ignition as indicated by tube temperature rise.

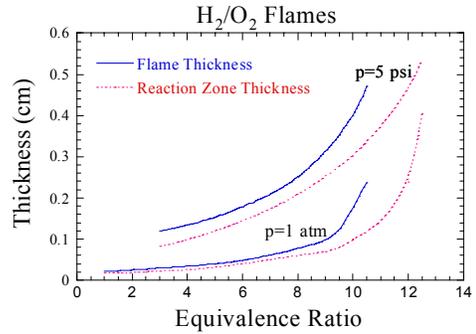


Figure 4. Plot of flame thickness and reaction zone thickness versus equivalence ratio for $p=1 \text{ atm}$ and 5 psia.

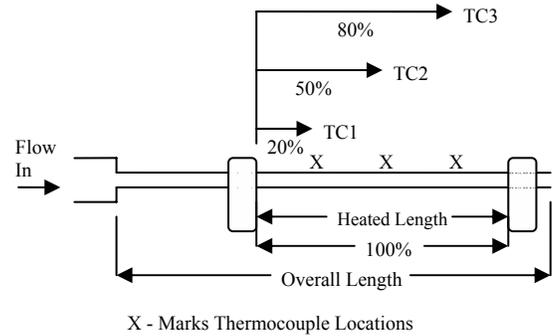


Figure 6. Schematic of microtube test articles.

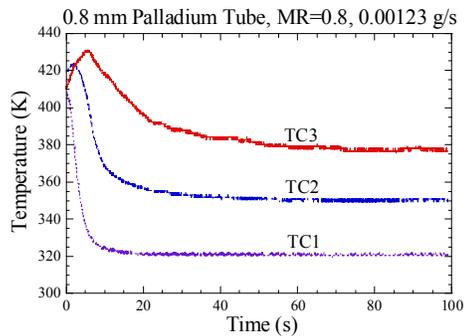


Figure 8. Non-ignition temperature data for 0.8 mm I.D. palladium tube, $MR=0.8$, 0.00123 g/sec.

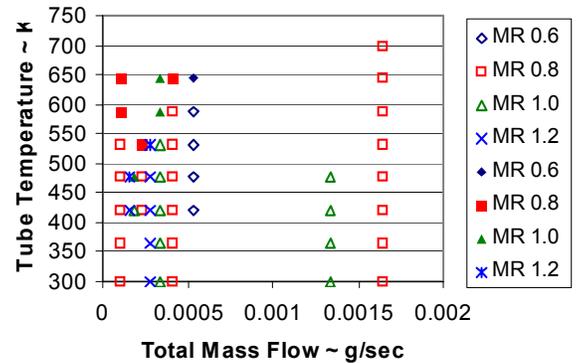


Figure 10. Ignition data for 0.4 mm I.D. platinum tube – open symbols are non-ignition and solid symbols are ignition as indicated by tube temperature rise.